The making of the Chandra X-Ray Observatory: The project scientist's perspective

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The history of the development of the Chandra X-Ray Observatory is reviewed from a personal perspective. This review is necessarily biased and limited by space because it attempts to cover a time span approaching five decades.

historical perspective | x-ray astronomy

It is sobering for me to realize that there are scientists who are working with data from this truly great observatory who were not even born when the foundation for what is now the Chandra X-Ray Observatory was laid. Thus, it may surprise many to know that the beginning was succinctly and accurately outlined in a research proposal that Riccardo Giacconi and colleagues wrote in 1963, a mere 9 months after he and his team's discovery of the first extrasolar x-ray source Scorpius X-1. As important, the data from this rocket flight also indicated the presence of the "diffuse x-ray background." Fig. 1 illustrates the showpiece of this insightful proposal. It shows a ≈1-m diameter, 10-m focal length, grazing-incidence x-ray telescope. The telescope was of sufficient area and angular resolution to determine the nature of the unresolved x-ray background. We all owe Riccardo an enormous debt of gratitude for his insight, leadership, and, in my case (and I suspect for many others), inspiration.

The resemblance between the early conceptual design shown in Fig. 1, and Chandra is no accident and is of importance in considering the way we (the scientific community) design our missions. Chandra was based only on achieving its scientific requirements, principally to be able to resolve the faint background sources. Chandra was not built on flying "what we can do." Neither in 1963 nor, indeed, in 1976—when Riccardo and his Co-Principal Investigator Harvey Tananbaum submitted their unsolicited proposal "For the Study of the 1.2 Meter X-Ray Telescope National Observatory"—did one actually know how to build the subarc-second telescope required to meet the scientific objectives. I feel it is important for one to know that these objectives were never compromised during the entire 23-year development, measured from the submission of this proposal to the launch in 1999. Nor did they lose their relevance during this time. This is in contrast to many [but not all (e.g., the Wide Field X-Ray Telescope)] missions, which suffer from what I call

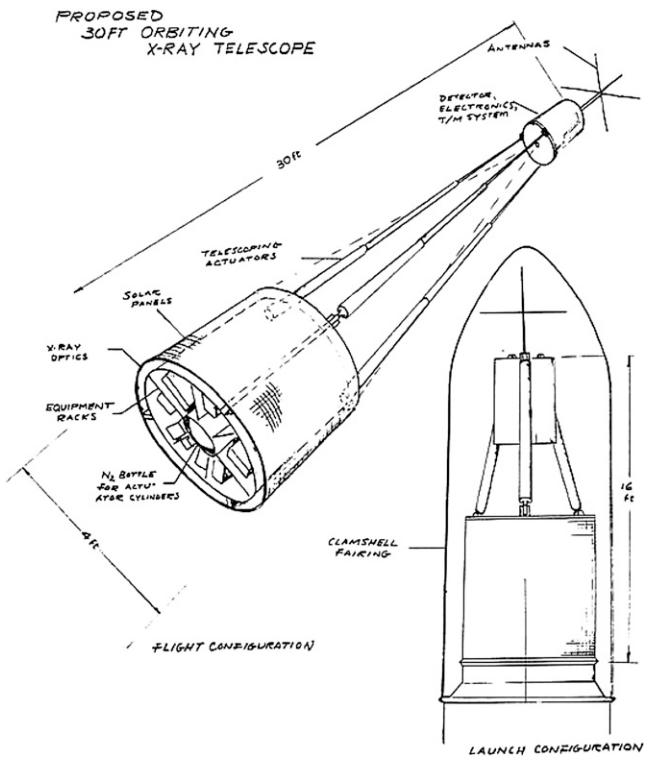

Fig. 1. Drawing from the 1963 proposal.

"cost-credibility paranoia," wherein one can only convince others of the cost reliability of the mission if one has essentially already built it. In too many cases, I feel this approach has forced one to compromise scientific objectives and to adopt a "we will build it, you will use it" approach to science. In these cases, too often are the scientific requirements adjusted to be compatible with the existing technology, as opposed to driving the technology. The approach is not terrible, because missions such as the Rossi Timing X-Ray Explorer have had, despite outdated technology, a high measure of success. Nevertheless, Chandra is an outstanding example of the power of the science-driven approach.

The proposal that Riccardo and Harvey submitted in 1976 drew attention at the National Aeronautics and Space Administration (NASA) headquarters, which then initiated a competition among the NASA centers to establish where such a mission might best be accomplished. In reaching a decision, NASA considered such factors as expertise, experience, manpower availability, and facilities. The Marshall Space Flight Center (MSFC) teamed with the Smithsonian Astrophysical Observatory (SAO), the Jet Propulsion Laboratory

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Fig. 2. The second Science Working Group. Left to right: A. Wilson [Interdisciplinary Scientist (IDS)], A. Fabian (IDS), J. Linsky (IDS), H. Tananbaum (head of the MST and ultimately Director of the Chandra X-Ray Center), A. Bunner (ex officio), S. Holt [X-Ray Spectrometer Primary Investigator (PI)], M. Weisskopf (Project Scientist), R. Giacconi (IDS), A. Brinkman (LETG PI), S. Murray (HRC PI), G. Garmire (ACIS PI), L. van Speybroeck (Telescope Scientist), C. Canizares (HETG/Focal-Plane Crystal Spectrometer PI), and R. Mushotzky (IDS).

teamed with the California Institute of Technology, and the Goddard Space Flight Center (GSFC) teamed with GSFC scientists in vying for the mission. I joined NASA in 1977, after the MSFC was assigned the responsibility for the mission. I did this with the understanding that Project Science was to be more than a single person and that the local project science team would be further supplemented by the group at the SAO, which became known as the Mission Support Team (MST). There can be no question that the outstanding success of Chandra is attributable, in no small part, to these arrangements.

The first Science Working Group of what was then called the Advanced X-Ray Astrophysics Facility was chaired by Riccardo. I served as Vice-Chairman. Other members and their affiliations were as follows: A. Opp (NASA headquarters; ex officio), E. Boldt (GSFC), S. Bowyer (University of California, Berkeley), G. Clark (Massachusetts Institute of Technology), A. Davidsen (The John Hopkins University), G. Garmire (California Institute of Technology), W. Kraushaar (University of Wisconsin, Madison), R. Novick (Columbia University), S. Shulman (Naval Research Laboratory), H. Tananbaum (SAO), A. Walker (Stanford University), K. Pounds (Leicester University), and J. Trümper (Max Planck Institut für Extraterrestriche Physik).

The peculiar name of the project, an "Advanced X-Ray Astrophysics Facility" (AXAF), was the inspiration of the NASA Associate Administrator at the time. He did not want to use the word "telescope" in describing a future program, because Congress had recently approved a telescope—what is now known as the Hubble Space Telescope (HST).

1979 saw the launch of the Einstein Observatory and its subsequent astounding impact on astronomy and astrophysics, namely, that all categories of objects from comets to quasars were x-ray sources and that study of their x-ray emission provides critical insights into such factors as emission mechanisms and evolution scenarios. This, in turn, led to the report of the Astronomy Survey Committee "Astronomy and Astrophysics for the 1980s," which recommended an AXAF as the number one priority for large spaced-based missions. The recommendation was more profound than one might imagine, because there was only one x-ray astronomer (George Clark) on the committee. Despite this superlative recommendation, it would take almost two decades before Chandra was launched. Although there were numerous reasons for this slow advance, and I am oversimplifying, Chandra appeared to need to wait its turn while the HST was being developed. We see this pattern reemerging as the International X-Ray Observatory appears to need to await the completion of the James Webb Space Telescope (JWST). A famous Nobel Prize winner has referred to the apparent delays in some programs caused by financial overruns and technical problems of other missions as "the punishment of the innocent," in a recent white paper to the current Decadal Survey.

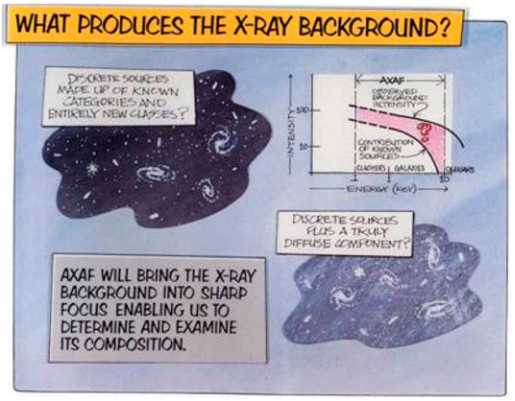
WHAT PRODUCES THE X-RAY BACKGROUND?
DISCRETE SOURCES MADE UP OF KNOWN CATEGORIES AND ENTIRELY NEW CLASSES?
AXAF
INTENSITY
ENERGY (keV)
DISCRETE SOURCES PLUS A TRULY DIFFUSE COMPONENT?
AXAF WILL BRING THE X-RAY BACKGROUND INTO SHARP FOCUS ENABLING US TO DETERMINE AND EXAMINE ITS COMPOSITION.

Fig. 3. A page from the AXAF brochure of 1985.

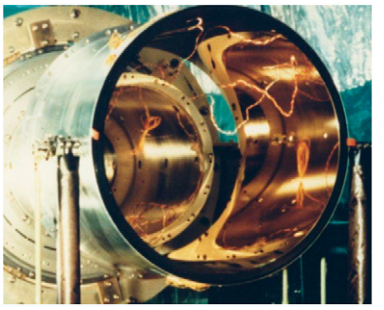

Fig. 4. The gold-coated TMA.

1983 saw the release of the announcement of opportunity for the first set of instrumentation (the "first set" because the AXAF was envisioned as being serviceable at that time). Experiment selection took place in 1985, and a second Science Working Group was formed, which I chaired and whose members and are pictured in Fig. 2.

The selected instruments included the Advanced Camera for Imaging Spectroscopy (ACIS); the High-Resolution Camera (HRC); the Low-Energy Transmission Grating (LETG); the High-Energy Transmission Grating (HETG); the Focal-Plane Crystal Spectrometer, which was removed during a descoping exercise in 1988; and the X-Ray Spectrometer, which was moved to a mission named the AXAF-Spectroscopy (AXAF-S) in 1992 before cancellation of the AXAF-S by Congress in 1993.

In addition to pursuing mirror and detector technology development during the 1980s, many of us became salesmen and brochure writers to gain full support for the program at NASA and in Congress. I will not speak here of the heroic role played by the Director of our science center, Harvey Tananbaum. There can be no question that we all owe him a huge debt of gratitude. Of course, Harvey was not the only one who helped to create this program. Others, such as Charles Pellerin and Arthur Fuchs at

Fig. 5. The XRCF at the MSFC. The building to the left houses the x-ray sources, filters, and monochromators. In the building on the right is the large thermal vacuum chamber, at a distance of 525 m from the source building. The chamber accommodates the Chandra 10-m focal length and full illumination of the 1.2-m-diameter optics.

NASA headquarters and our industrial allies, also played a significant role. It may seem inappropriate to some, but it is definitely true that accomplishment of "big money science" requires many skills. The scientific excellence of the mission is necessary but, unfortunately not sufficient. One of our most successful endeavors in this time frame was a brochure, a page of which is illustrated in Fig. 3. A facing page (not shown) was designed for the intelligent layman with an inset for our colleagues in the scientific community. The cartoons (one is shown in Fig. 3) were jokingly described as being aimed at NASA officials and members of Congress. Nevertheless, these cartoons were scientifically accurate and drew attention. The brochure not only won an artistic prize but made a positive impression where it was needed. During this period, the Space Station was included as an ingredient in the servicing of Chandra. For a number of technical and programmatic reasons, this tie-in soon disappeared.

The late 1980s saw significant technical progress. Two versions of what we called the "Technology Mirror Assembly" (TMA) were built and x-ray tested. The assembly was composed of a single paraboloid-hyperboloid pair. The TMA was a two-thirds scaled version of the most challenging (the innermost) AXAF mirrors. At a two-thirds scale, the focal length became 6 m, which allowed for testing in the existing X-Ray Calibration Facility (XRCF) at the MSFC. This facility had been built to calibrate and test the Einstein x-ray optics.

The TMA-1 was received July 27, 1985, and the angular resolution was better than 0.5 arc-seconds. However, to our chagrin, near-angle scattering attributable to mid-frequency errors had a negative impact on the encircled energy. We had made the cardinal mistake of assuming that we need not be concerned about errors on the millimeter-scale lengths that were the culprits, because we had not envisaged that the tools and processes we were using could introduce terms at those frequencies. Of course, we changed our technical approach and removed these errors. The TMA-2 was received January 6, 1989, and is shown in Fig. 4. The performance of the TMA-2 was outstanding with respect to all specifications and convinced us that the Chandra optics could be built successfully. It is interesting to know that, 20 years later, the TMA-2 is still the best x-ray telescope in the world considering only angular resolution and encircled energy.

Unfortunately, our critics did not agree that we knew how to build the optics and imposed on us the challenge of manufacturing the largest set (paraboloid-hyperboloid) of AXAF optics and demonstrating that the performance would meet requirements. In his eagerness to comply with this challenge, which would become a congressional mandate, the Associate Administrator of NASA promised that not only would we build and test these mirrors using the optical metrology we had verified by x-ray testing the TMA but that we would also perform the necessary x-ray tests. Moreover, he committed us to accomplish this by the summer of 1991. Unfortunately, the plan and funds to enhance the existing XRCF were not compatible with this schedule.

NASA always seems to work best in a crisis. The Director of the MSFC took it upon himself to manage the effort, which meant meetings once a week at 7:00 AM in his office. Despite the early hour, the Director's intervention meant that all the

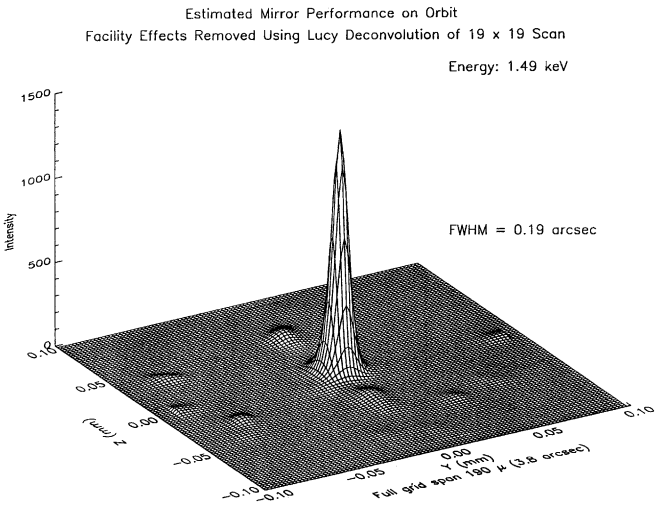

Fig. 7. Performance of the Verification Engineering Test Article deconvolved to remove the effects of a finite-sized source at a finite distance and showing the on-orbit performance. The FWHM is 0.19 arcseconds. Both the FWHM and the encircled energy were well within specifications.

Fig. 6. The Verification Engineering Test Article.

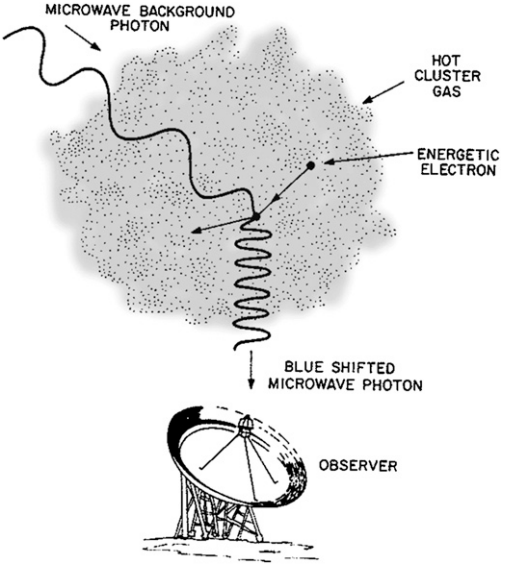

Fig. 8. The SZ effect.

Fig. 9. Consolidated Array for Millimeter AstRonoMy.

resources of the center were available to us and without (most of) the usual bureaucratic holdups that occur when one wants to do something quickly. In my oral presentation, I showed a number of slides that documented the development of the XRCF. The interested reader may find these on the Web. Fig. 5 shows the completed facility. The XRCF is currently being used for visible-light cryogenic testing of the JWST beryllium mirrors.

Fig. 6 shows the Verification Engineering Test Article, comprising the largest paraboloid-hyperboloid pair but uncoated and uncut to their final length, and thus not in the flight mount. Testing took place in 1991 and, after compensating for the finite distance, the size of the x-ray source, and gravitational effects, produced the outstanding result shown in Fig. 7.

The project's reward for this fantastic effort was to have the following year's budget cut, necessitating another launch delay. Despite all the progress, both in the optics and concurrent instrument development, the launch of Chandra had been postponed at the pace of 1 year per calendar year for many years. Something had to be done.

The outcome of about a year of grueling discussions and trade studies as to the details of the mission was to abandon servicing. To convince the powers-that-be that servicing was not lurking in the background as a hidden variable, low-earth orbit was also abandoned. (It is interesting to contemplate the potential servicing of Chandra in the future when NASA develops vehicles capable of traveling to the moon and Mars. It is also sobering to realize that Chandra's first servicing would have been scheduled around the time of the Columbia accident.)

Abandoning low-earth orbit had numerous implications, some positive and some negative. The negative aspects included the sacrifice of two of the six nested telescopes (as part of the weight reduction program necessitated by the much higher orbit) and the loss of servicing and instrument replacement. Another consequence turned out to be the establishment and subsequent loss of the AXAF-S mission, which accommodated the extremely heavy x-ray calorimeter. This mission was canceled in 1993 by Congress, which suggested that the calorimeter be flown on a Japanese mission, albeit with poorer angular resolution than had been planed for the AXAF-S. One benefit from the redesign was the switch of the telescope coating from gold to iridium. This change retained the higher energy effective area despite the removal of two mirrors. Another benefit was improved efficiency for observing afforded by the orbit. This orbit reduced both the debilitating effects of occultation by the Earth and the amount of time spent in the radiation belts. The tremendous decrease in the number of occultations of the sun by the Earth also greatly simplified the thermal design of the observatory.

The very early 1990s also saw the selection of the Chandra X-Ray Center (CXC), after an open competition for an organization to serve as the interface between the observatory and the community. This early selection would guarantee that the organization could (and would) influence the design and development of Chandra and be in place in time to be challenged to analyze independently data taken during x-ray calibration. Because Chandra would be much more scientifically powerful than previous missions, it needed to be thoroughly and precisely calibrated.

An important and little known development took place as part of the Chandra program in 1992. This marked the beginning of the efforts by John Carlstrom (California Institute of Technology at the time) and Marshall Joy (Project Science at the MSFC) to use millimeter-wave interferometry as a tool to measure the Sunyaev–Zeldovich (SZ) effect (Fig. 8), where photons from the 3° microwave background are Compton-scattered by the hot x-ray-emitting electrons that pervade the intracluster medium. The scientific project of the Telescope Scientist, Leon van Speybroeck, was based on the recognition that for relaxed clusters, where the assumption of hydrostatic equilibrium was reasonable, one could simply combine x-ray measurements of the gas temperature and cluster size with SZ measurements to determine the distance. The only difficulty, even as late as 1992, was that the SZ measurements were extremely difficult to accomplish. Thus, it was natural for the Chandra program and the MSFC to sponsor this development.

With the advent of the interferometric techniques and the subsequent development of arrays specifically designed for these observations, such as the Consolidated Array for Millimeter AstRonoMy (Fig. 9) and the South Pole Telescope, Chandra spawned another scientific "industry" and was able to achieve Leon's objectives and more.

In the fall of 1996, the flight mirrors, fully cut, coated, aligned, and mounted (known as the High-Resolution Mirror Assembly) arrived at the MSFC for x-ray testing and calibration. X-ray calibration was extremely important for a number of reasons. First, the calibration activity would verify, beyond any doubt, that the optics had been built (as it turned out) to much better than their specifications. Second, and more important, the performance characteristics of the optics and the optics in conjunction with the flight instruments were calibrated to various degrees of precision as called for in a huge calibration requirements document prepared by the scientific participants. (Many have mistakenly thought that all Chandra calibration requirements were to be at the 1% level. The 1% value is mistakenly quoted out of context from the overall

Fig. 10. Photograph of a typical daily meeting in the conference room at the XRCF. Clockwise: hands of S. O'Dell (Project Science), S. Wolk (CXC), C. Jones (CXC), R. Carlsen (TRW), D. Jerius (MST), and the back of the head of D. Dewey (HETG).

Fig. 11. Lower row: Eileen M. Collins, Mission Commander; Michel Tognini, Mission Specialist. Upper row: Steven A. Hawley, Mission Specialist; Jeffrey S. Ashby, Pilot; Catherine (Cady) G. Coleman, Mission Specialist.

Fig. 12. Lalitha Chandrasekhar with a model of the observatory.

requirement of the observatory to calibrate accurately).

Additional benefits of calibration included providing a database of flight-like data, and thus an early test of the Principal Investigator's and CXC's ability to deal with flight-like data. Additional benefits were the camaraderie and friendship that developed as scientists, engineers, and managers from the various different teams (e.g., MSFC Project Science, SAO MST, HRC, ACIS, LETG, HETG, MSFC Project Management, MSFC Engineering, TRW, Ball Aerospace, Eastman Kodak) worked together "24/7" throughout the longer than 6-month period (Fig. 10). The experience was a major contributor toward changing people's perception of each other, particularly in becoming "we" as opposed to "us and them."

Subsequent to x-ray testing, the focal-plane detectors went to Ball Aerospace in Colorado for integration and testing into the module that houses them and provides the linear translations used both to switch instruments and to provide focus adjustment. These mechanical drives, which we

Fig. 13. At the Chandra control center. Left to right: J. Olivier (Deputy Project Manager), C. Canizares (HETG PI), S. Murray (HRC PI), H. Tananbaum (CXC Director), J. MacDougal (MSFC Chief Engineers Office), and R. Schilling (TRW Deputy Project Manager).

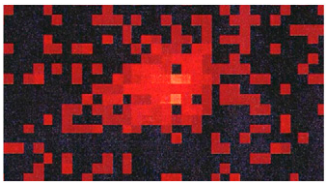

Fig. 14. Raw image of "Leon X-1." The data were not yet corrected for S/C motion, and the detector was not yet at best focus.

worried about a lot before launch, have now worked routinely thousands of times throughout the mission. This Science Instrument Module (SIM) was then delivered to the TRW in California for integration into the spacecraft (S/C) and for system-level testing.

System-level testing, both at the SIM and S/C level, brought on a number of technical and programmatic challenges. One of most notable was the failure of the vacuum door that protected the ACIS instrument to open during the thermal vacuum test. A second involved compromised printed wiring boards that required the project to delay the launch by many months while the appropriate electronics were removed from the S/C, replaced, retested, and reintegrated. We all owe a large debt of gratitude to Michael Hirsch at the TRW for forcefully bringing this problem to everyone's attention.

In the spring of 1999, the observatory was delivered to the Kennedy Space Flight Center for integration with the inertial upper stage (IUS) and subsequent integration into the cargo bay of Columbia. The IUS is a solid-rocket two-stage engine that would boost Chandra toward its present orbit. The combined Chandra-IUS system became the heaviest payload ever launched by a shuttle. The activities surrounding the launch were themselves very interesting. The Commander of Columbia was Eileen Collins, the first woman to hold such a position. She, along with her crew, is pictured in Fig. 11. Eileen drew a lot of attention and special visitors. Not only did the First Lady, Hillary Clinton, come to visit but the singer Judy Collins wrote, composed, and then sang: "And we will fly beyond the sky. Beyond the stars, beyond the heavens. Beyond the dawn we'll carry on. Until our dreams have all come true. To those who fly, we sing to you." Perhaps as important from our perspective was the press's attention to Eileen. This attention minimized the number of times we were asked if this telescope would have problems such as the HST initially experienced. Of course, we could answer that the telescope had been successfully tested and calibrated.

Other notables at the launch included Lalitha Chandrasekhar (Fig. 12), who read a poem she had composed and noted that Subramanyan Chandrasekhar, after whom the observatory is named, would not have enjoyed all the fuss. The male model Fabio also attended under the false assumption that he had been invited by the astronaut Cady Coleman. The invitation had been jokingly issued in her name by her fellow crew members.

It took three attempts to launch the shuttle. These occurred just past midnight on the mornings of July 20, 22, and 23, 1999. The successful launch was challenging for the astronauts because of a hydrogen leak and an electrical short that took place shortly after the rockets fired. The calmness of the astronauts through these major glitches was testimony to their courage and ability. Placement into

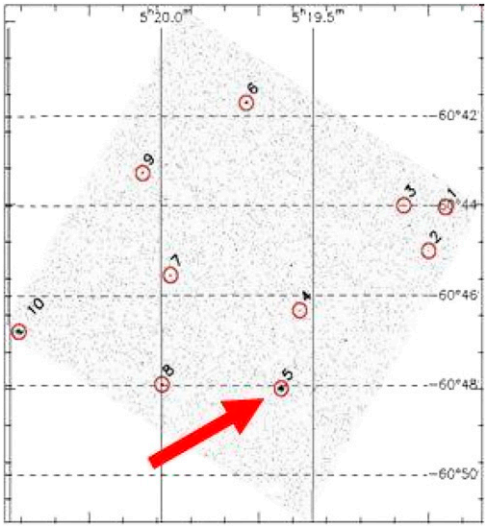

Fig. 15. The full "first-light" image on the ACIS-S3 after aspect correction. The bright source indicated by the red arrow is "Leon X-1," a type 1 AGN at z = 0.3207.

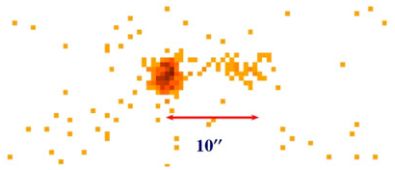

Fig. 16. Image of Parkes 0637-752 and its x-ray jet.

low-earth orbit was only the beginning for us of many tense days before we could be sure that the observatory was working properly. Just 8 h into the mission and after the successful deployment from Columbia, we required the successful operation of the IUS. Although this system had an excellent track record, the previous use of an IUS had failed, albeit for reasons that we understood and were confident would not reoccur. Still, one worried. Obviously, the IUS successfully fired and placed the observatory near its final orbit. Then followed the use of Chandra's own propulsion system, which was fired five times over many days to achieve the final orbit. Of course, activation and checkout were taking place in parallel. Perhaps the event that was most intense was the opening of the door to the ACIS in view of the previously mentioned failure during testing. The ACIS team made a number of technical and operational changes to the door mechanisms and provided more robust opening procedures, but we were unsure that we really understood the root cause of the previous failure. One can imagine that we were very nervous during the opening process. Fig. 13 shows a partial view of the control center during the commissioning, and one can see the concentration on people's faces during these times.

The observatory was launched with S3, the better of the two ACIS back-illuminated CCDs, at the prime focus. Which instrument to place at the focus during launch was the result of much discussion. We wanted to assure a powerful scientific mission in the event that, for some reason, the SIM motions failed, thereby preventing changing instruments.

On August 12, 1999, the last door preventing the optics and the ACIS from viewing the universe was opened. The true "first-light" Chandra image is shown in Fig. 14. The raw ACIS image of the brightest source on S3 told us, by inspection (because the flux was concentrated into a handful of AXIS pixels, each subtending 0.5×0.5 arc-seconds), that the observatory was operating more or less as expected, even before establishing best focus. Of course, we now know that the observatory is performing as predicted. The full S3 field is shown in Fig. 15. The bright source that we dubbed "Leon X-1" turned out to be a type 1 active galactic nucleus (AGN) at a redshift of $z = 0.3207$. The ubiquity of the AGN in x-ray images was not a surprise but certainly a forerunner of the fabulous discoveries that Chandra was about to make.

The next tasks in the commissioning process were to test the aspect system and to determine the best focus for the ACIS-S. Our target was a bright AGN, selected because we wanted a bright point source. Fig. 16 shows the image and highlights the discovery of an x-ray jet, an accidental but certainly exciting outcome. Moreover, the angular resolution of Chandra allowed the use of these data to determine the best focus. Another Chandra "test image" produced a fruitful scientific result. The now famous image of the Crab Nebula, its pulsar, and the remarkable structure showing the shock produced by the pulsar wind was another spectacular result from such a test.

Now, we are celebrating 10 years of outstandingly successful scientific research with this great observatory. There can be no question as to its success, whether measured in terms as mundane as publications, citations, and PhD theses, for example, or more profoundly by producing such results as the clarification of the mechanism producing the x-ray emission from comets, the resolution of the diffuse background, the independent and confirmatory measures of the Hubble constant, and constraining the equation of state of the universe. In 47 years, we have been privileged to participate in the advancement of a discipline that has moved from discovery of a single extrasolar x-ray source to the detection of sources ≈10 orders of magnitude fainter. The smiles of those pictured in Fig. 17 are as applicable today as they were at the time one saw the earliest Chandra images.

Fig. 17. Observing the official first light on August 19, 1999, at the control center. Right to left: M.C. Weisskopf, T. Aldcroft, C. Grant, H. Tananbaum, R. Brissenden, M. Bautz, M. Freeman, F, Baganoff, and K. Gage.

Those interested in more information on making the Chandra X-Ray Observatory should see the book by Wallace and Karen Tucker (1).

ACKNOWLEDGMENTS. We all owe a debt of gratitude to the many people who contributed to Chandra's success, including the US taxpayers, who, through their government, have had the courage and insight to foster such important research.

1. Tucker W, Tucker K (2001) *Revealing the Universe: The Making of the Chandra X-Ray Observatory* (Harvard Univ Press, Cambridge, MA).